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SUMMARY

The present studies involved the use of a single-stage research compressor without stators which has been adapted to an outdoor test setup to obtain some basic inlet noise data. The objectives of the study were to investigate the effects of inlet duct geometry (such as length of duct and duct resonators) on the radiated noise of this compressor for a range of tip speeds, pressure ratios, and blade loading conditions. The data are presented in the forms of radiation patterns, frequency spectra, and pressure time histories.

A significant reduction in noise level was obtained by increasing inlet duct length and also by using an inlet resonator. The radiation patterns for the overall noise were nearly circular. However, the noise pressures analyzed at the blade-passage frequency exhibited lobed patterns. The spectra of the noise contained two broad noise peaks and some discrete frequency harmonics of the blade-passage frequency. Amplitude modulations similar to those for other single- and multiple-stage axial-flow compressors are evident in the time histories of the discrete blade-passage frequency.

INTRODUCTION

Compressor noise constitutes a serious problem in connection with the operation of commercial jet-powered aircraft, and this problem has been aggravated by the conversion to a turbofan type of power plant for which the compressor and fan components of the engine are more powerful. One factor that causes the noise to be annoying is the presence of discrete frequency components associated with the rotating machinery. These discrete frequency components are, in many cases, at frequencies to which the ear is very sensitive. Compressor noise of aircraft engaged in take-off and landing is judged to be objectionable, but is most serious during the landing approach operations because, even though the engines are operating at partial power, the aircraft, because of established approach procedures, is closer to the people on the ground than during take-off.

The compressor noise problem can be conveniently considered in two parts; namely, the generation of the noise by rotating machinery in a duct, and the radiation of this noise from the duct. Several research studies have been made which relate to one or both of these aspects. (See refs. 1 to 12.) The present studies were designed to obtain information relating to the latter aspect of the problem, that is, the effect of inlet duct geometry on the noise radiated from a compressor. This effect was accomplished by making use of a large single-stage axial-flow compressor without stators as the noise source. The inlet configurations investigated with this compressor incorporated various duct lengths and duct resonators. Information was obtained for a range of operating conditions of the compressor. The noise data are presented in the forms of radiation patterns, frequency spectra, and pressure time histories.

APPARATUS AND METHODS

Description of Test Setup

The general physical arrangement of the axial-flow compressor and drive motor is shown in figure 1. The compressor consisted of a single rotor wheel mounted in an airflow duct of annular shape. An important feature of this equipment is a provision for changing the duct geometry upstream of the rotor. Also, it is important to note that the rotor was operated in the free duct and that no stators were used in any of the tests.

The rotor configuration consisted of 20 blades having a root diameter of 24 inches and a tip diameter of 34 inches. A photograph of the rotor wheel is shown in figure 2. A mechanical breakdown during the investigation necessitated the use of a second rotor wheel which differed from the first only in blade airfoil section. In each case the blade chord length was approximately 4 inches, with rotor 1 having an NACA 65-010 airfoil section and rotor 2 having a special NACA 65-series airfoil with a more highly cambered section. Because of the different airfoil sections, the two rotors had different blade loading characteristics as indicated by the data of figure 3. Mass flow in pounds of air per second is plotted as a function of rotor tip speed in feet per second for these two rotors. In general, rotor 2 had a higher loading at a given rotor speed than rotor 1.

The compressor was driven by a 3,000-hp variable-speed electric motor at speeds up to 110 rps, which corresponded to a maximum rotor tip speed of 980 ft/sec.

Provisions for changes in the duct geometry upstream of the rotor included the various duct configurations shown in figure 4. These variations involved changes in the duct length between the inlet and the rotor plane from 4 feet to 16 feet, as indicated in figure 4(a). In addition, a resonator section as illustrated in figure 4(b) was provided in connection with a 4-foot duct length. The resonator, basically a tuned Helmholtz resonator, was designed by using the procedures given in reference 13 (pp. 21-25) for maximum effectiveness at 70 percent of the compressor rotational speed.

The equipment was set up in an open area several hundred feet from the nearest large reflecting surface other than the ground surface (fig. 5). The control console and recording equipment were located about 100 feet distant in a small building. Noise surveys were made at ground level around 30- and 60-foot-radius azimuth circles extending from near the inlet center line to a position opposite the discharge. Provision was made for a shielding wall, as indicated in figure 5, in an attempt to minimize the noise from the discharge at the stations for which noise data were obtained.

Instrumentation

Ten commercially available condenser microphone systems having a usable frequency response range from about 5 cps to 10,000 cps and a flat frequency response (within ±2 dB) in the range from 10 to 7,000 cps were used for all measurements. These systems were calibrated with a 400 cps sine wave at a pressure level of 121 dB. The microphones were spaced at 15° intervals from -30° to 105° for rotor 1 tests, as shown in figure 5. For the tests of rotor 2, sound recordings were obtained with the aid of a single microphone that traversed the range of azimuth angles, -15° to 105°. (See fig. 5.) The microphones were mounted at ground level with diaphragm oriented parallel to the ground. The output signals were recorded on a multichannel FM tape recorder having a usable frequency range from 0 to 10,000 cps. For purposes of analyses, the tape recordings were played back into a one-third octave band analyzer and a graphic level recorder.

Input power to the compressor and the compressor rotational speed were recorded. Static and total pressures in the duct and downstream of the rotor were obtained with the aid of static pressure taps and a total pressure rake connected to a multitube manometer which was photographed during the run.

Operating Procedures

Noise data and performance data were obtained for all inlet duct configurations through a range of compressor tip speeds for both rotors. The data runs were of the order of 1- to 2-minute duration to permit satisfactory tape recording of the noise data and photographic recording of the manometer data. The tape recordings have been analyzed and data are presented in the forms of radiation patterns, frequency spectra, and pressure time histories. Test runs were obtained for surface wind conditions of less than 15 knots.

RESULTS AND DISCUSSION

Basic Characteristics of Noise

Before the effects of duct geometry on the radiated noise are examined, it is desirable to look at the basic noise characteristics of the single-stage axial-flow compressor. An indication of the characteristic radiation pattern shapes for the overall noise produced by this compressor for a range of operating conditions is shown in figure 6 for the 4-foot duct. The data were obtained on a 30-foot-radius azimuth circle from the inlet duct for three tip-speed conditions. It can be seen from the results of figure 6 that the overall noise radiation patterns tend to be circular to within about ±3 dB. The most obvious result is the increase in noise level with increasing rotor tip speed. Increasing tip speed for a given rotor is associated with an increase in blade loading. Increasing blade loading for a constant tip speed has the effect of increasing the noise pressure level. In the present tests, however, the effects of tip speed and blade loading could not be separated.

The spectral content of the noise as a function of azimuth angle is shown in figure 7. Shown in the figure are one-third octave band spectra (from rotor 1) for measuring stations at azimuth angles of 0°, 45°, and 90°. Three main features of these spectra can be noted. First, a broad random noise peak occurs at the low frequency in the vicinity of 100 cps. This noise peak is higher in amplitude at the 0° azimuth position (in front of the compressor) than at the other locations. The midfrequency of this broad-band noise peak is in the range of the resonant frequencies of the central cavity which the inlet center body (fig. 1) encloses. A broad random noise peak also occurs at higher frequencies in the vicinity of 1,000 to 3,000 cps, the amplitude of which is lower in front (0°) than to the side (90°). This broad random noise peak occurs roughly in the frequency range predicted by the following expression from reference 14 for vortex shedding from the rotor blades:

$$f = K \frac{u}{d}$$

where K is the Strouhal number, u is the stream velocity, and d is the width of the blade. Finally, an indication of discrete frequencies superposed on the random noise spectra is noted. These discrete frequencies are present for each of the various measuring locations shown and are believed to be associated with the blade passages of the rotor. The lowest discrete frequency appears to be at the fundamental blade-passage frequency. Also appearing are harmonics of this fundamental frequency. The noise characteristics shown are believed to be associated with the geometry of this particular setup.

Effects of Duct Geometry

The effects of duct length between the inlet entrance plane and the rotor plane, and also the effects on the radiated noise of a peripheral array of resonating chambers between the inlet and the rotor plane, are illustrated in figures 8 and 9.

In figure 8, sound-pressure levels obtained at a radius of 30 feet are plotted for various azimuth angles. These data were obtained with the compressor operating at a constant speed and for the two inlet duct lengths of 4 feet and 16 feet. Figure 8(a) shows overall levels and figure 8(b) shows levels obtained in the one-third octave band containing the fundamental blade-passage frequency. The overall noise radiation patterns are generally circular in shape, and a reduction of 7 dB with increasing duct length from 4 to 16 feet is indicated. Although the radiation pattern of the overall levels is circular and apparently not affected by inlet duct length, at the fundamental blade-passage frequency the radiation patterns depart from the circular shape and exhibit lobes. Again a decrease (about 10 dB) in noise level with increasing duct length is observed.

Tyler and Sofrin (ref. 1) pointed out that a compressor generates spinning modes that travel along the inlet duct, and that the transition point from decay to propagation of these spinning modes is called cut-off Mach number. This cut-off Mach number is a function of rotor tip speed, number of rotor blades, relative number of rotor blade and stator vanes, and hub-tip ratio. For the rotor used in the investigation, the cut-off Mach number is estimated to occur at a rotor tip Mach number of 1.11. (See ref. 1.)

It should be pointed out that the reduction in noise level with increasing duct length, as well as the absence of lobes on the radiation pattern, would vary for tip Mach numbers above cut-off Mach number. Since this investigation was with a rotor alone, the trends shown may not be representative of a rotor operating in conjunction with a stator.

Radiation pattern measurements similar to those of figure 8 were obtained with a 4-foot duct length in which a peripheral array of resonating chambers was incorporated. (See fig. 4.) These results are presented in figure 9. The resonators were designed to operate at the blade-passage frequency of the rotor associated with a tip speed of 623 ft/sec. In figure 9(a) it can be seen that the overall noise levels associated with the resonator configuration are lower (by about 4 dB) than those for the plain duct. Approximately the same reductions were noted over a range of azimuth angles. Much larger reductions (10 dB), however, were noted to occur for the discrete frequency component near the design frequency of the resonator, as indicated in figure 9(b). It can also be seen that the lobes of the radiation pattern are sharply defined for the resonator configuration.

Amplitude Modulation of Compressor Noise

In the current studies and also in some measurements obtained on other single- and multiple-stage axial-flow compressors, an apparent amplitude modulation of the noise was observed as indicated in figure 10. Time histories of the noise pressure in the one-third-octave band containing the fundamental blade-passage frequencies for four different axial-flow compressors are given in the figure. Examination of the time history of noise pressure for the present investigation of the single-stage axial-flow compressor (fig. 10(a)) indicates that amplitude modulation occurs, but not in an orderly time sequence. This modulation suggested the possibility of significant wind effects on flow conditions in the inlet. Similar results were also observed from measurements during the operation of multiple-stage axial-flow compressors, as indicated by the traces of figures 10(b) and 10(c). An investigation of a similar nature for a single-stage research compressor operating in a special acoustically treated test cell resulted in similar modulation of the noise as shown in figure 10(d). This latter result corresponded to a condition of nearly uniform flow, thus inflow variations due to cross winds as a source of these noise pressure variations were minimized. In references 10 and 11 similar amplitude modulations were observed during operation of a single-stage research compressor, and such modulations were ascribed to the mixing of random and discrete noise tones.

SUMMARY OF RESULTS

Inlet noise studies conducted on a 34-inch-diameter single-stage axial-flow compressor without stators in an outdoor setup for a range of operating conditions and inlet geometries indicate the following results:

1. Reductions of up to 7 dB in overall noise level and up to 10 dB at the fundamental blade-passage frequency were obtained by increasing duct length from 4 to 16 feet.

2. Reductions of up to 4 dB in overall noise and up to 10 dB at the fundamental blade-passage frequency were obtained with the use of an inlet resonator at the rotor tip speed for which it was designed.

3. For all inlet configurations, the overall noise radiation patterns were found to be nearly circular, whereas the discrete frequency noise exhibited lobes.

4. The spectra of the noise contained two broad noise peaks in the vicinity of 100 cps and 1,000 to 3,000 cps, and some discrete frequency harmonics of the blade-passage frequency.

5. The time histories of the discrete blade-passage frequency noise exhibited amplitude modulation similar to that noted for other single- and multiple-stage axial-flow compressors.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 15, 1964.

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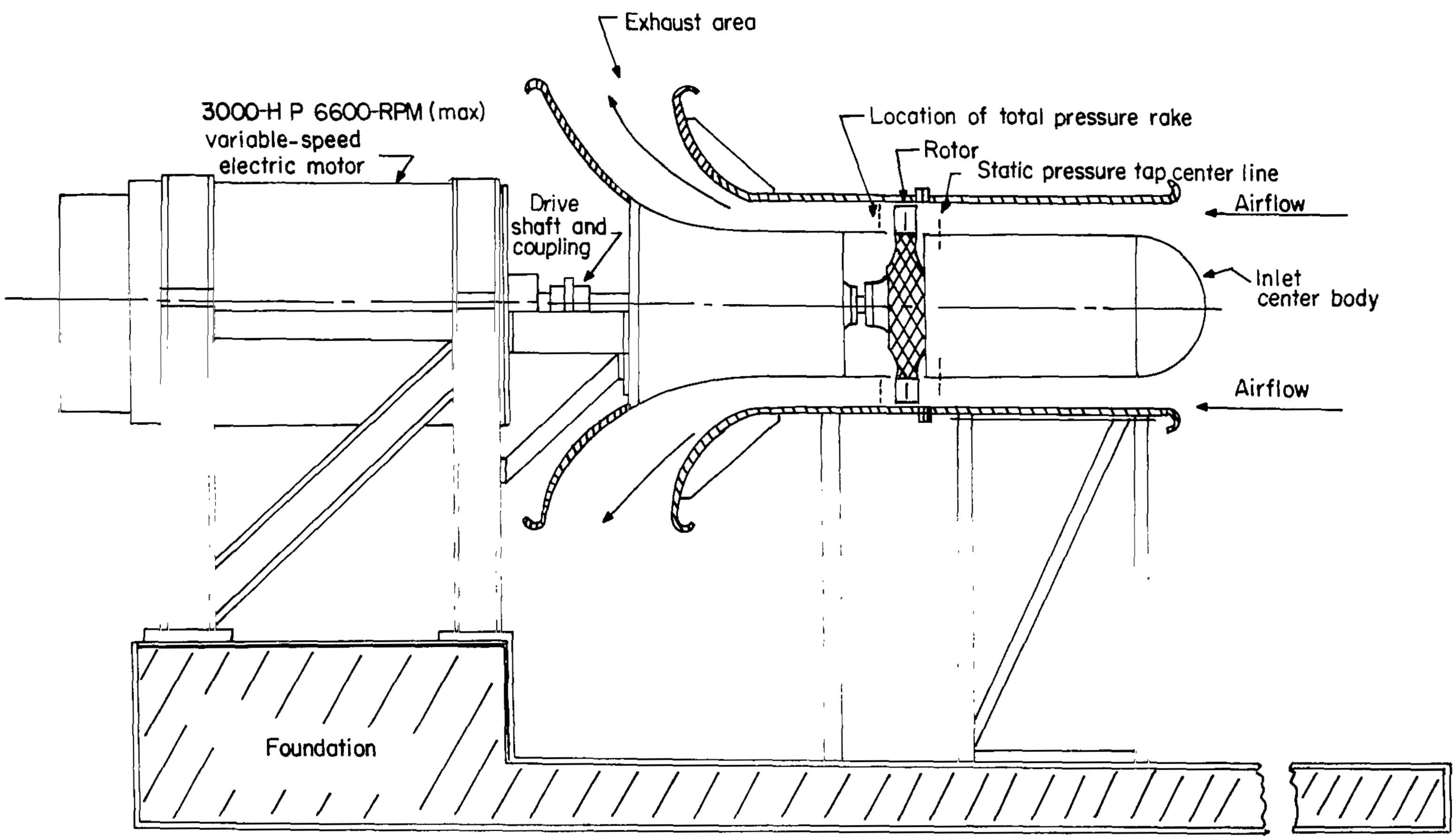


Figure 1.- Schematic sketch of compressor and drive motor setup used in tests.

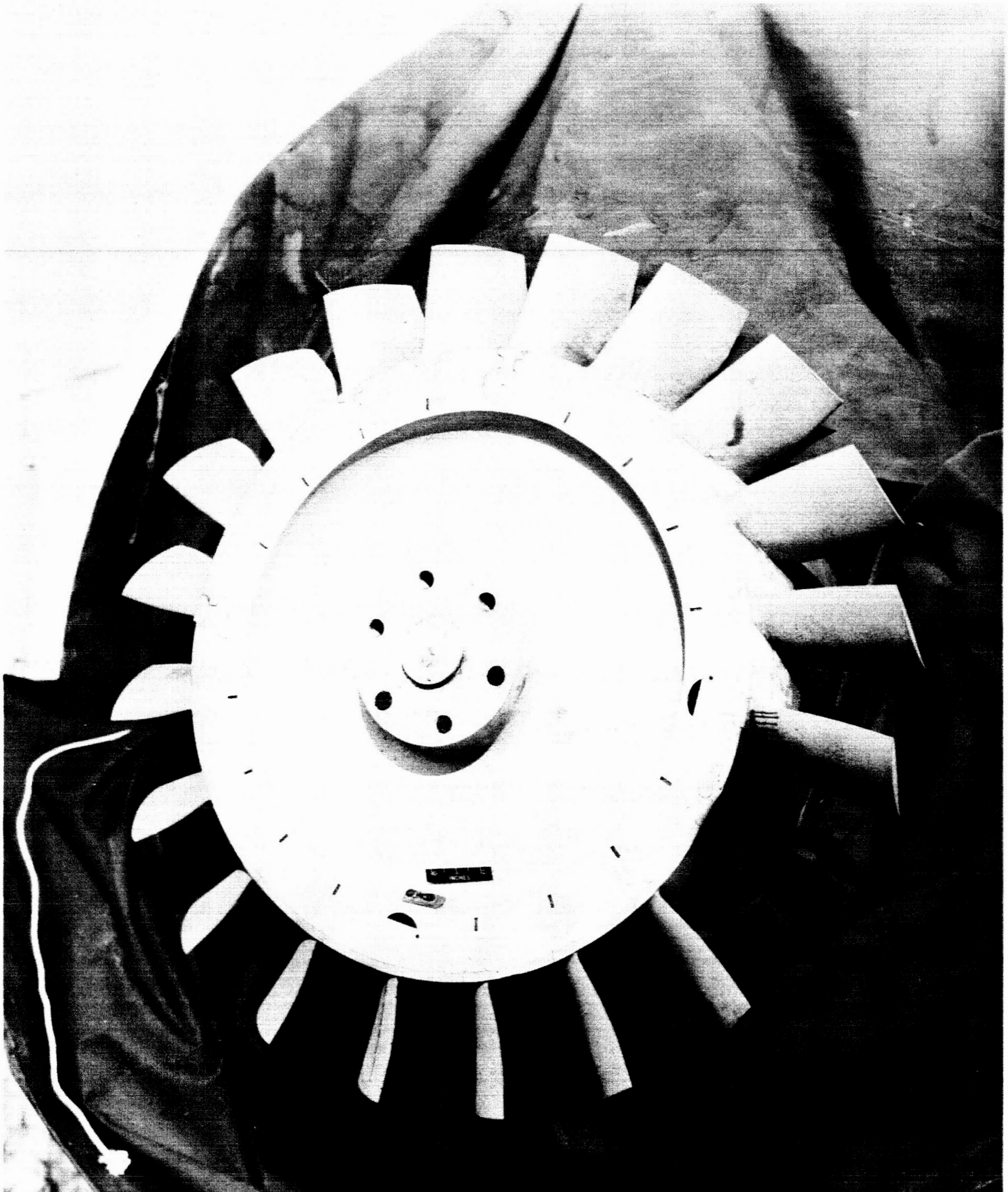


Figure 2.- Photograph of rotor 2 wheel assembly (20 blades). L-63-10009

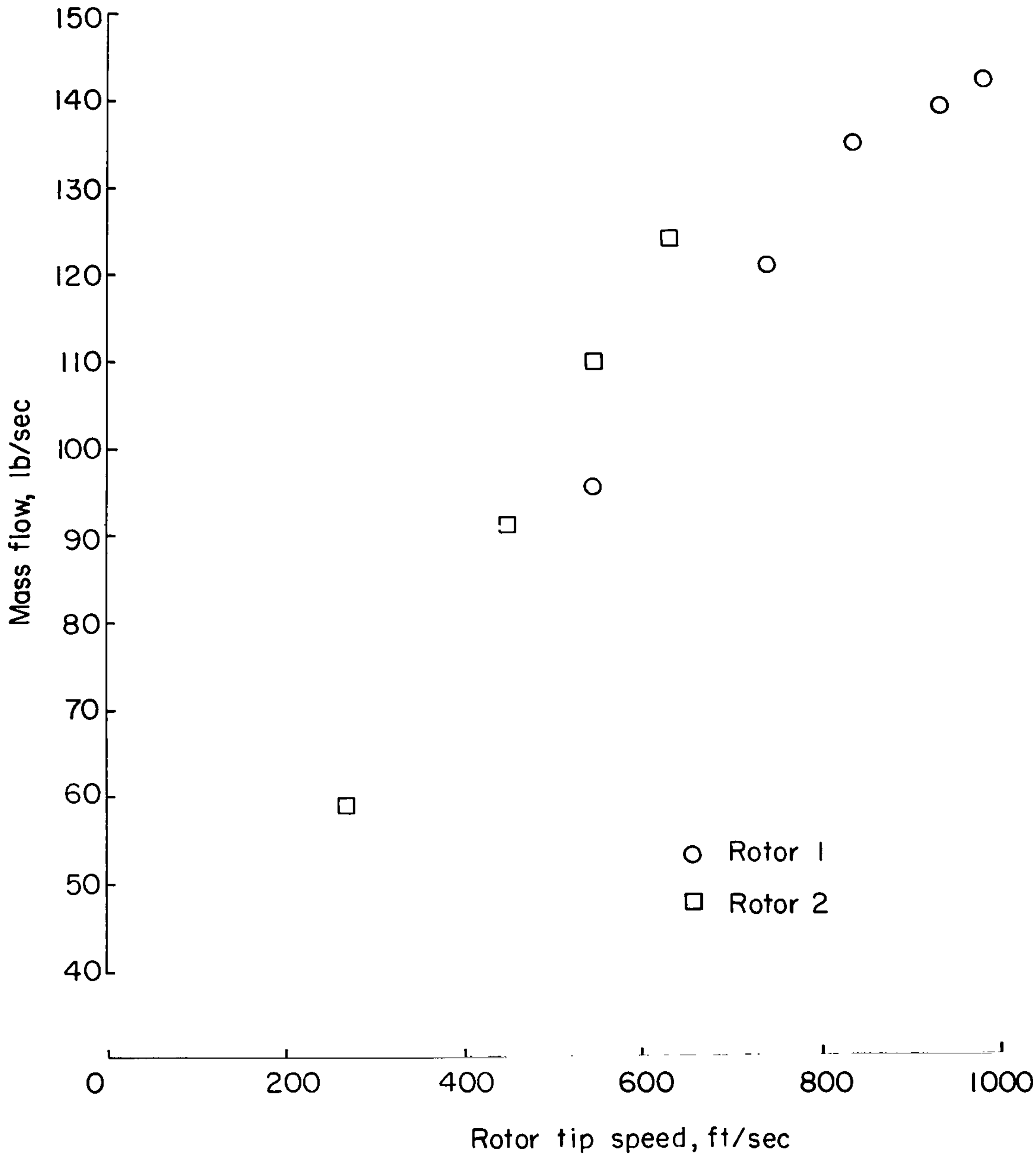
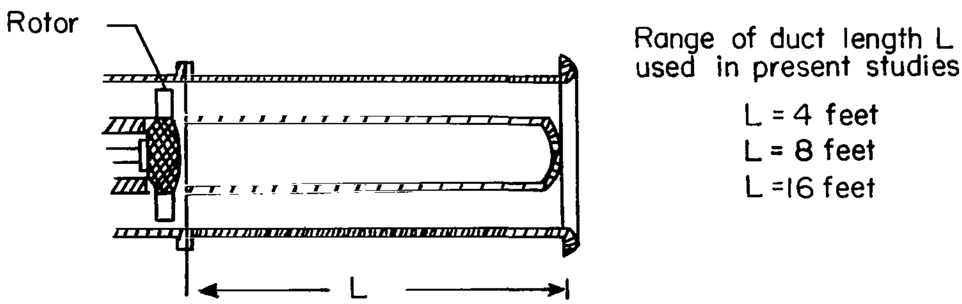
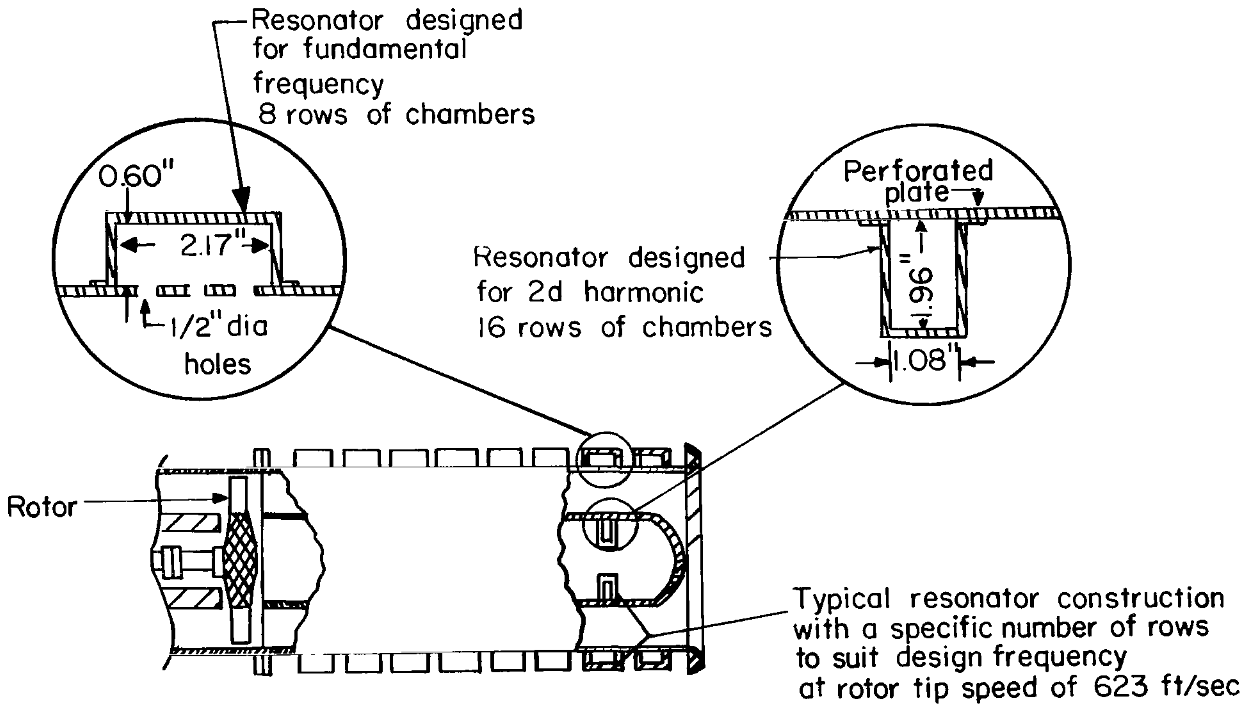


Figure 3.- Comparison of mass flow as a function of rotor tip speed for rotor 1 and rotor 2.



(a) Plain duct.



(b) Resonator.

Figure 4.- Schematic sketch of various duct configurations used during tests.

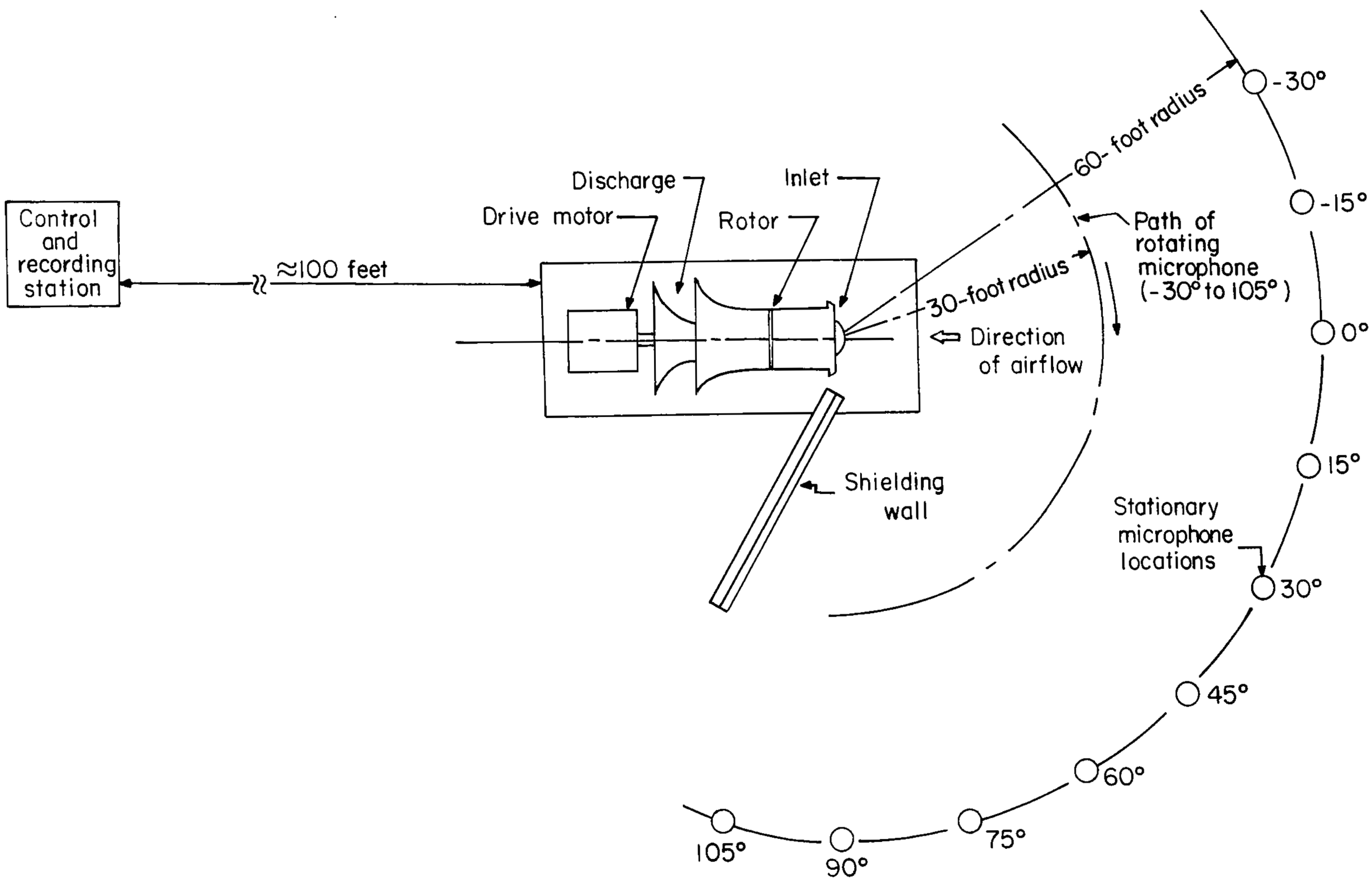


Figure 5.- Plan view showing general arrangement of equipment and microphone locations.

	Tip speed, ft/sec	Mass flow, lb/sec	Pressure ratio
△	267	59.0	1.02
□	445	91.0	1.07
○	623	123.5	1.11

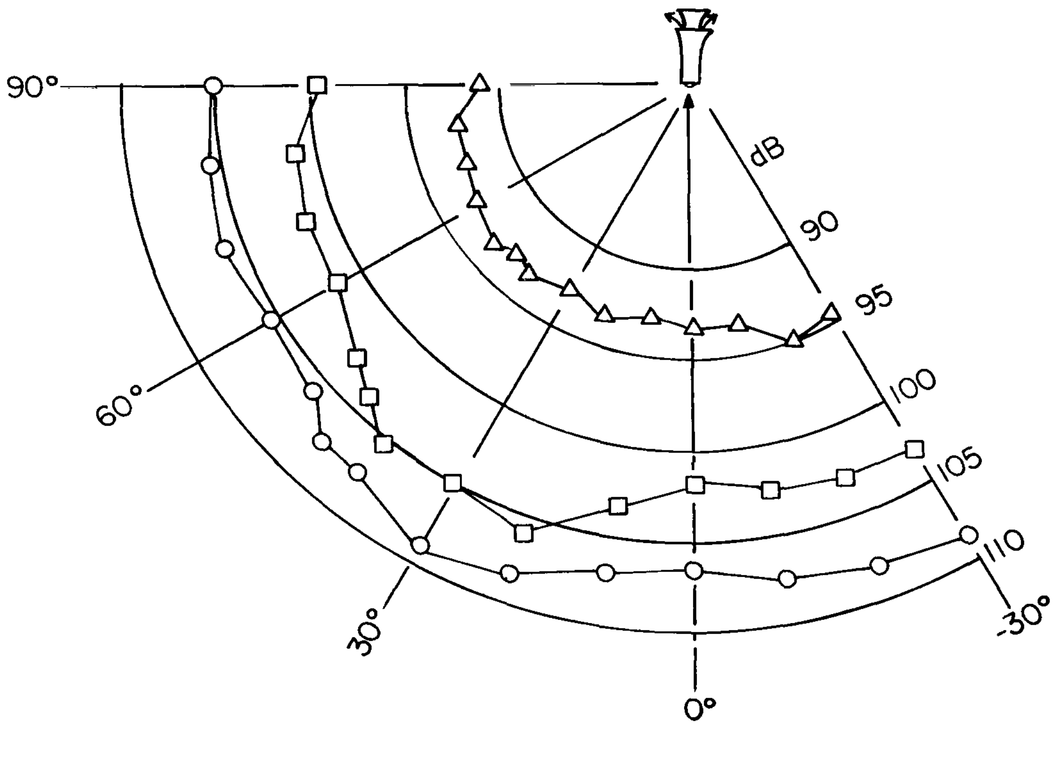
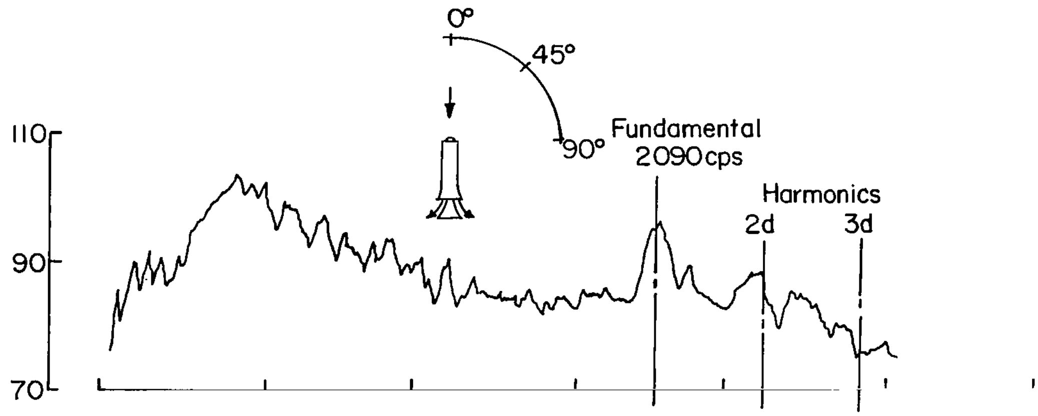
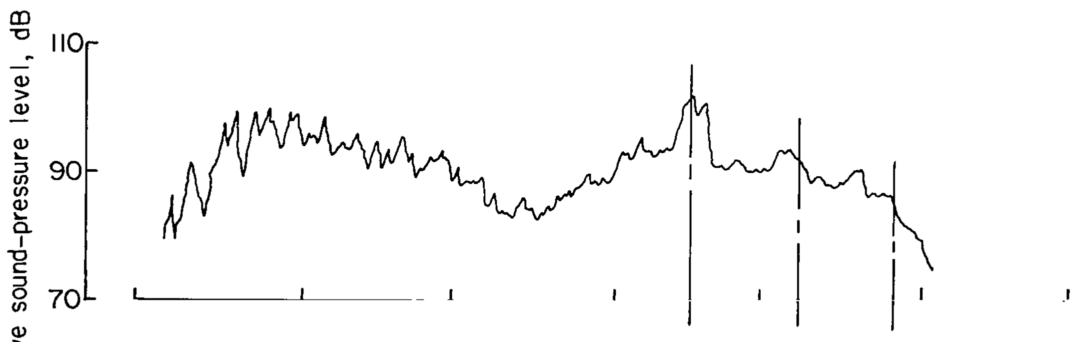


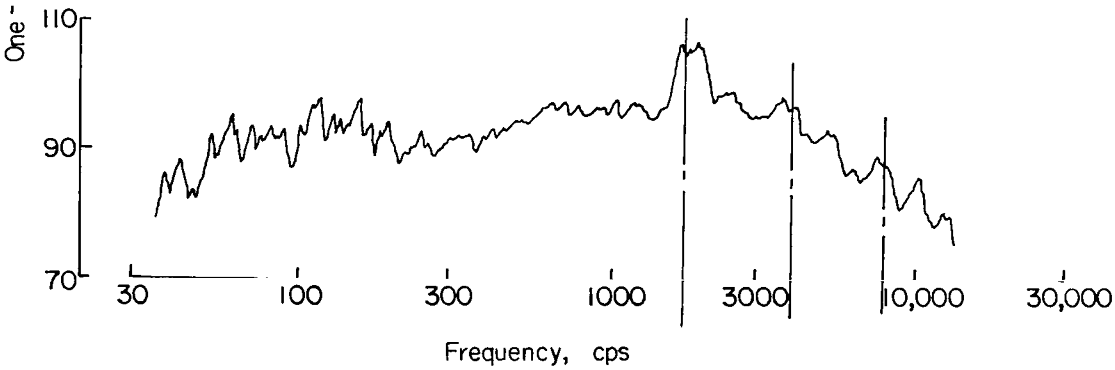
Figure 6.- Overall-noise radiation patterns produced by rotor 2 operating at various tip speeds. Measured on 30-foot radius; 4-foot inlet duct.



(a) 0° position (directly ahead of inlet).



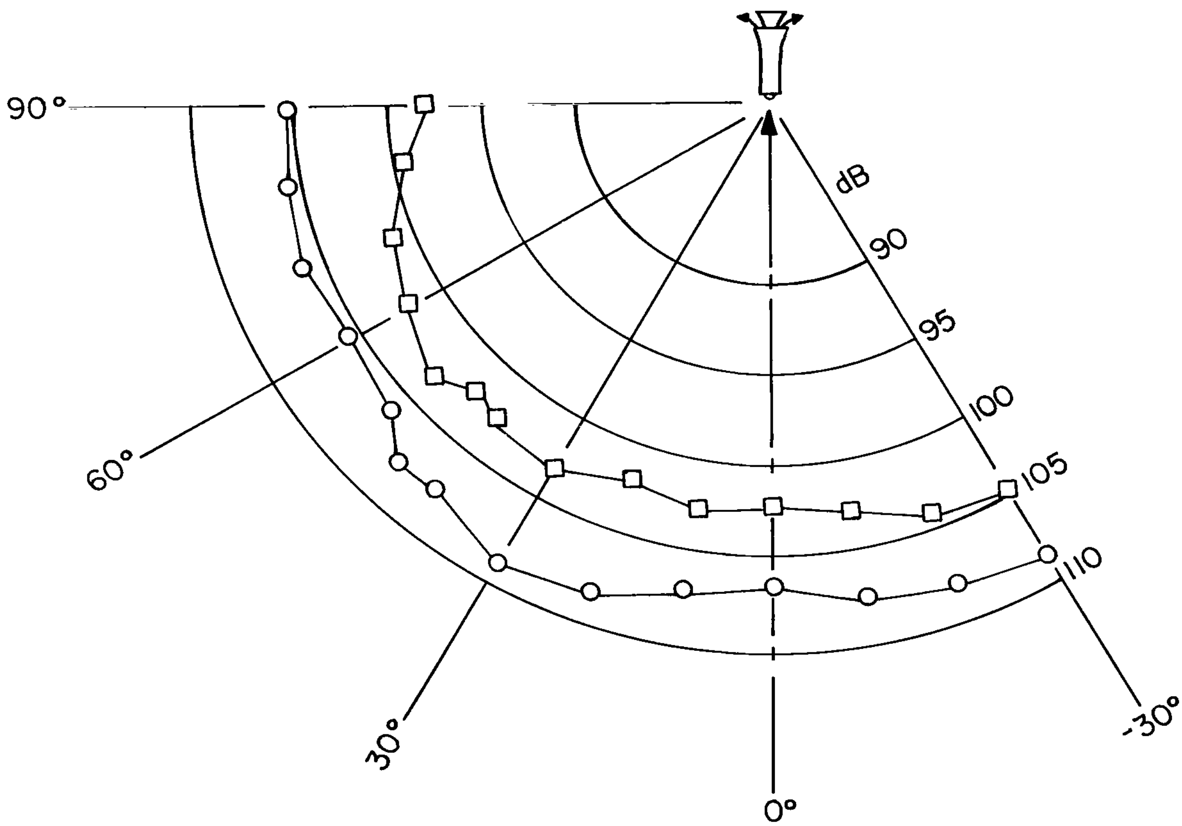
(b) 45° position.



(c) 90° position (perpendicular to inlet center line).

Figure 7.- Noise spectra at various azimuth angles for rotor 1 operating at a tip speed of 931 ft/sec (104.5 cps). Measured on 60-foot radius; 8-foot inlet duct.

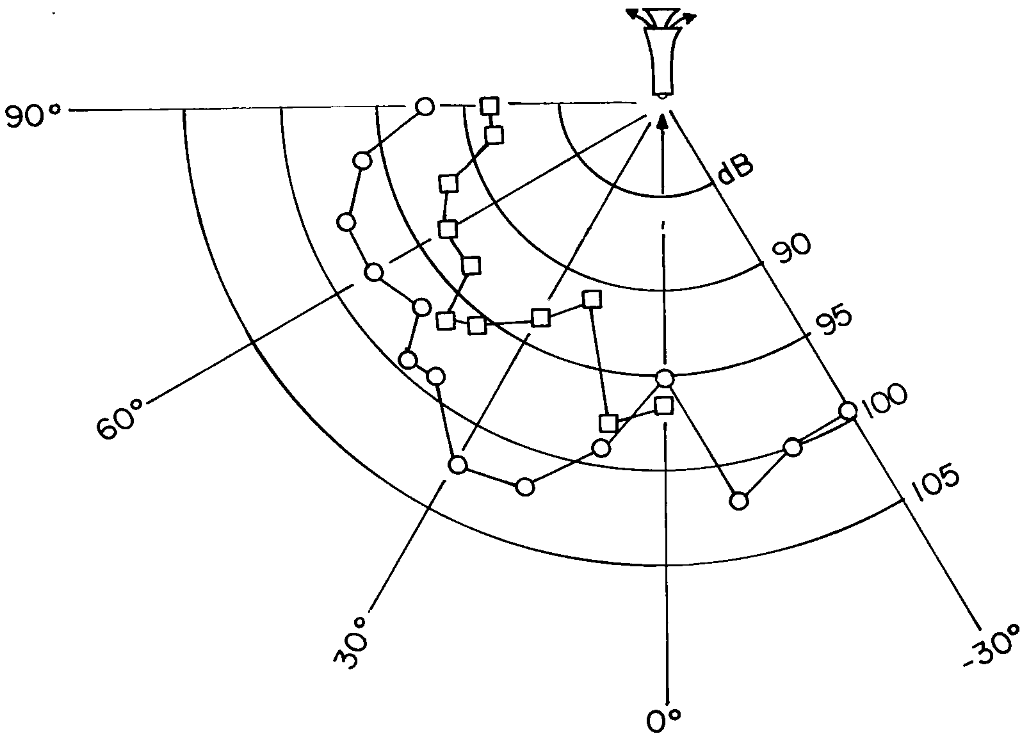
	Duct length, ft	Mass flow, lb/sec	Pressure ratio
□	16	125.0	1.11
○	4	123.2	1.11



(a) Overall sound-pressure levels.

Figure 8.- Effect of duct length on noise radiation patterns for rotor 2 operating at a tip speed of 623 ft/sec. Measured on 30-foot radius.

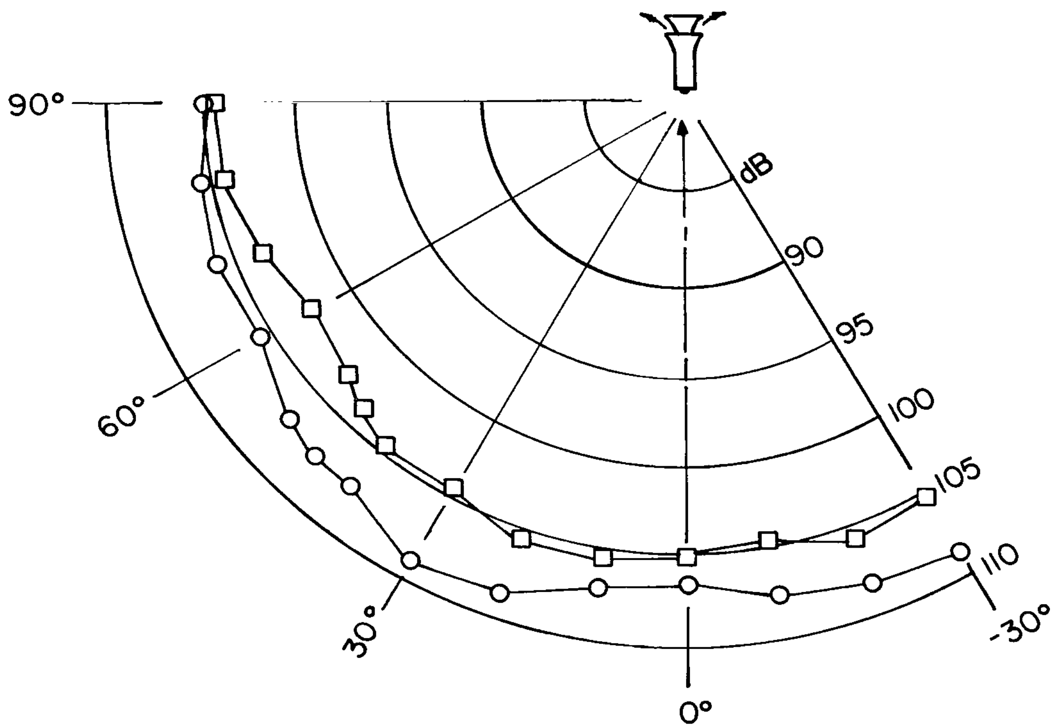
	Duct length, ft	Mass flow, lb/sec	Pressure ratio
○	4	123.2	1.11
□	16	125.0	1.11



(b) Fundamental sound-pressure levels.

Figure 8.- Concluded.

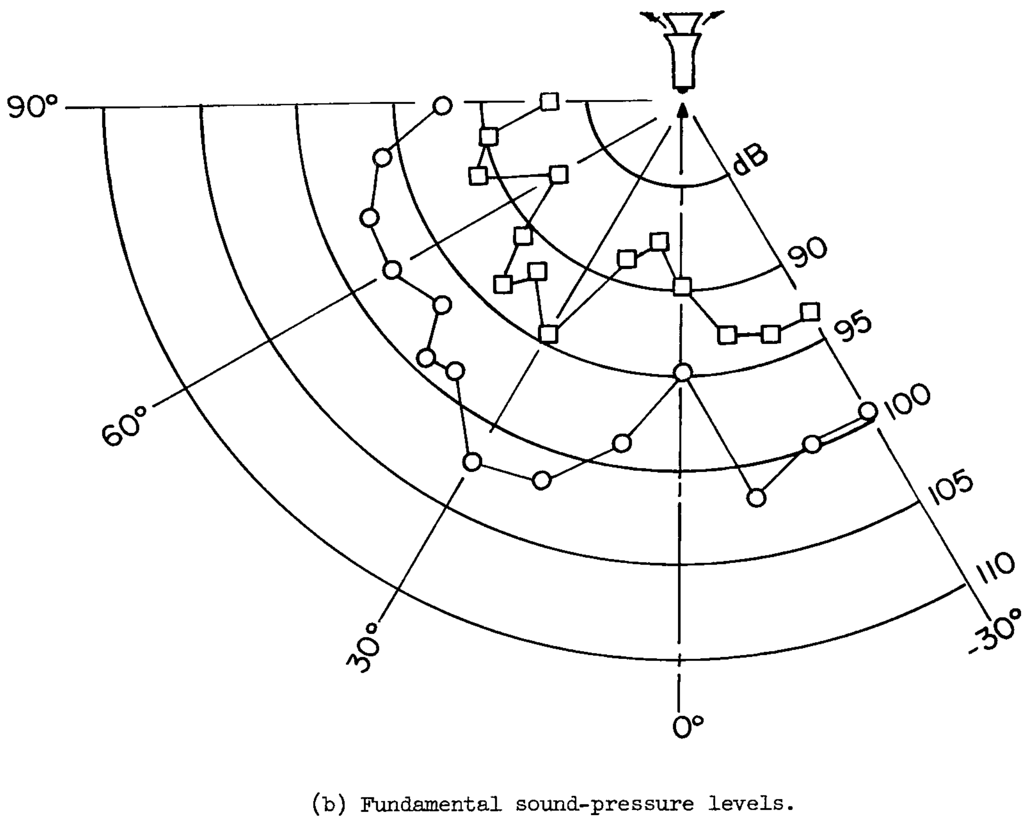
	Type Inlet	Mass flow, ft/sec	Pressure ratio
□	Resonator	125.5	1.09
○	Plain duct	123.2	1.11



(a) Overall sound-pressure levels.

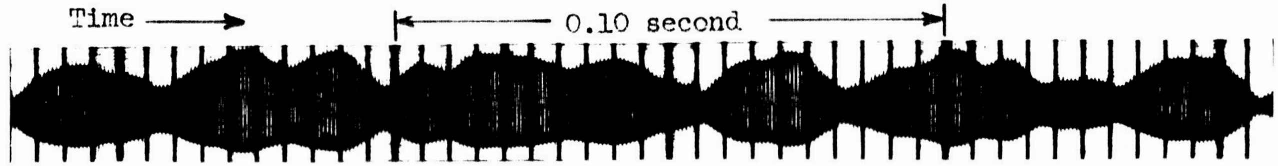
Figure 9.- Comparison of noise radiation patterns for a 4-foot inlet duct and a 4-foot resonator with rotor 2 at a tip speed of 623 ft/sec. Measured on 30-foot radius.

	Type inlet	Mass flow, lb/sec	Pressure ratio
□	Resonator	125.5	1.09
○	Plain duct	123.2	1.11



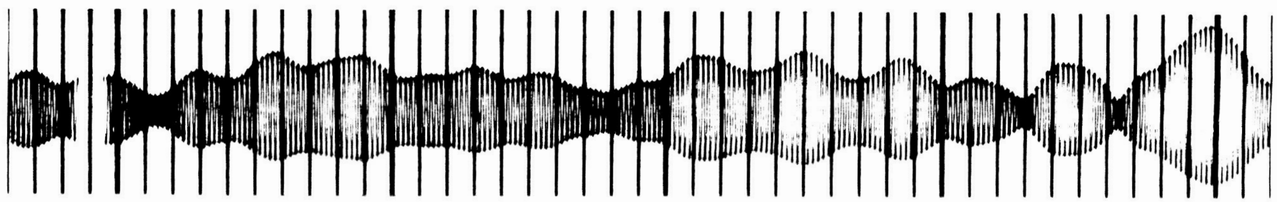
(b) Fundamental sound-pressure levels.

Figure 9.- Concluded.

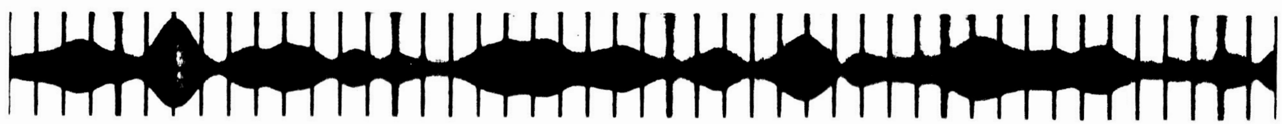


(a) 34-inch-diameter-rotor single-stage compressor; fundamental blade-passage frequency of 2090 cps; 30° azimuth measuring station.

(b) Jet-engine multiple-stage compressor; fundamental blade-passage frequency of 4700 cps; 30° azimuth measuring station.



(c) Military-fighter-airplane multiple-stage compressor; fundamental blade-passage frequency of 1100 cps; 0° azimuth measuring station.



(d) 14.75-inch-diameter-rotor single-stage compressor; fundamental blade-passage frequency of 6950 cps; 30° azimuth measuring station.

Figure 10.- Time histories of noise pressures in one-third octave band containing the fundamental blade-passage frequencies of four different axial-flow compressors.

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